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Photovoltaics for the Defense Community through Manufacturing Advances

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Photovoltaic solar power will bring a new level of self-sufficiency to the defense community, both for individual soldiers and military bases. Flexible photovoltaics integrated into tents and used as portable chargers can provide access to power in remote battlefield conditions.[1] To minimize reliance on supply chains, combining rechargeable batteries with portable photovoltaics could decrease the battery load weight of a soldier by half.[2] In addition, military bases that install photovoltaics will be able to implement micro-grid systems. Micro-grids combine self-sufficient energy generation with base-only electrical interconnection, making a base independent of the outside electrical grid and thus enabling a high degree of security and mission readiness.[3]

PHOTOVOLTAIC GRID PARITY

With these wide-ranging benefits, the relevancy of making photovoltaics more accessible for the defense community is clear. One of the ways to make photovoltaics more accessible is to decrease the cost of photovoltaic electricity to the point of grid parity, where solar electricity fed into the grid is the same cost as conventional sources (e.g., coal, nuclear, natural gas, etc.). In fact, achieving photovoltaic grid parity by 2015 has been stated as a goal for the US Government through the Department of Energy (DOE) Solar Energy Technologies Program*. The DOE estimates that in the US, achieving unsubsidized photovoltaic grid parity will require system costs to come down 50-70% from the levelized cost of energy (LCOE) benchmarked in 2005 (see Figure 1).

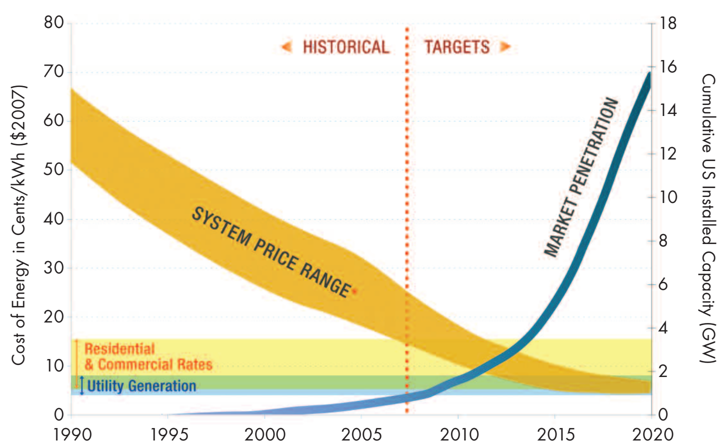
The way to determine the point of grid parity is to calculate the LCOE of a photovoltaic system and compare it to the local electric rates. The LCOE (¢/kilowatt-hour) is the sum of the costs of the system divided by the amount of energy it produces during its lifetime. It can be calculated with the formula below:†

$$LCOE = \text{net present value}\frac{(\text{price})}{(\text{energy})} = \text{Initial investment}[\$/\text{Watt}] + \frac{\sum_{n=0}^{N} \frac{\text{Maintenance costs }[\$/\text{kilowatt - hour}]}{(1+\text{discount rate }[\%/\text{ year}])^{n}}}{\sum_{n=0}^{N} \frac{\text{Annual electricity generated }[\text{kilowatt} - \text{hour / year}]}{(1+\text{discount rate }[\%/\text{ year}])^{n}}}$$

The initial investment is often broken down to isolate the module, the inverter, and the balance of system (BOS) costs. The module is the "solar panel" component that generates electricity, the inverter converts direct current (DC) produced by the module to grid-ready alternating current (AC), and the BOS represents all the other initial costs, which include wiring between modules, racks to mount modules, and installation labor.

A module's value balances two factors: the cost of manufacturing the active semiconductor materials, wire connections, packaging, etc., and the power that the module can generate from sunlight. As discussed in the subsequent section, different module technologies and their associated manufacturing techniques offer different but viable module solutions. For instance, some module manufacturing costs may be promising because they are very low, but they may produce a module with lower performance. Alternatively, some module configurations use some very high cost components, but those components convert sunlight to power with high efficiency. Modules do not represent the only way to decrease the initial investment required for photovoltaic installations, but they are currently around 50% of the initial outlay and for the near future will continue to be a target for reducing LCOE.

To get an idea of the effect of a 50-70% decrease in LCOE, it is useful to compare the present situation to a reasonable forecast. In Figure 2, a map shows the difference in LCOE for residential photovoltaic systems bought at $8.50/W and electric rates across the US. In areas where high grid electricity prices, excellent sunlight, and/or state and local incentives are present in some combination (red and orange), photovoltaics are already financially competitive.‡



Market Sector	Current US Market Price Range Cost (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Figure 1. **Historic and predicted photovoltaic cost of energy and total installations over time.**

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14. ABSTRACT
Photovoltaic solar power will bring a new level of self-sufficiency to the defense community, both for individual soldiers and military bases. Flexible photovoltaics integrated into tents and used as portable chargers can provide access to power in remote battlefield conditions. To minimize reliance on supply chains, combining rechargeable batteries with portable photovoltaics could decrease the battery load weight of a soldier by half. In addition, military bases that install photovoltaics will be able to implement micro-grid systems. Micro-grids combine self-sufficient energy generation with base-only electrical interconnection, making a base independent of the outside electrical grid and thus enabling a high degree of security and mission readiness.

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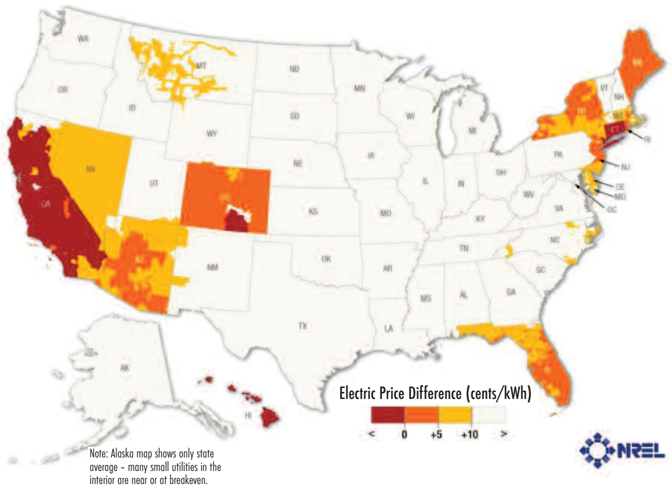

Figure 2. **Difference in electricity prices in 2007 between solar levelized cost of energy and grid electricity.**

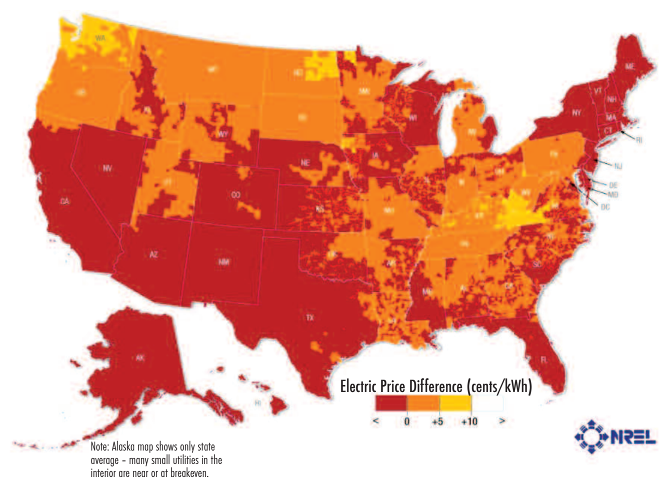

Figure 3. **Projected difference in electricity prices in 2015 between solar levelized cost of energy and grid electricity.**

In Figure 3, a further comparison for residential photovoltaic systems bought at $3.30/W shows a realistic forecast for 2015, assuming no state or local incentives for residential photovoltaic installations and real electricity rate increases of 2.5% per year.[§] In this scenario, the price difference between grid electricity and photovoltaic electricity would be less than 5¢/kWh for 91% of sales in nearly 950 of the largest utilities, indicating that grid parity would be achievable for most of the nation by 2015.

MANUFACTURING AND PHOTOVOLTAIC COST

In the private sector, the prospect of selling a product with desirable attributes at a price that puts it in the reach of a market of hundreds of billion dollars or more has fueled an enormous investment of funds in photovoltaic companies through public stock offerings, venture capital (VC), and private equity (PE) (see Figure 4). There are two reasons DOE and the private sector believe grid parity within six years is an achievable target. First, the considerable diversity in photovoltaic technologies and within the manufacturing options for each particular technology has produced a number of viable options for decreasing module costs. Second, further scale-up of manufacturing capacity will achieve significant cost reductions based on economies-of-scale and industry-wide lessons learned, much like the semiconductor industry has enjoyed. Many of these photovoltaic companies claim the potential to meet unsubsidized grid parity in the largest markets in the 2012-2015 timeframe.

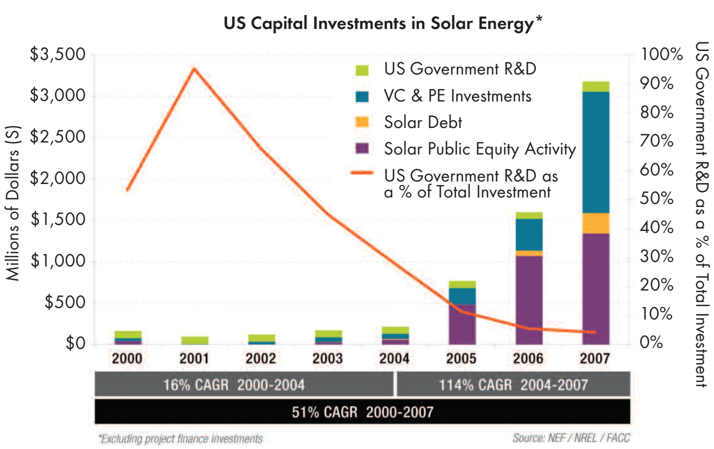

Figure 4. **Surge in solar energy investment.**

Photovoltaic Manufacturing Diversity

There are three major groups of photovoltaic module technologies currently in the marketplace:

- Crystalline Silicon
- Thin Films
- Concentrating Photovoltaics (CPV)

In Figure 5, module technologies are binned into these three groups, and then at the next two levels divisions show how the secondary categories can be further differentiated through materials choices, manufacturing techniques, and engineering designs. The three major types of photovoltaics currently available are highlighted in Table 1. Conceptually, this highlights the rich design space of photovoltaic systems and suggests multiple pathways may achieve grid parity.

Crystalline silicon photovoltaics are the most mainstream style of photovoltaic module. This technology represents 80-85% of the newly added capacity in 2008. The most common way to manufacture a crystalline silicon module is to pull or cast a silicon

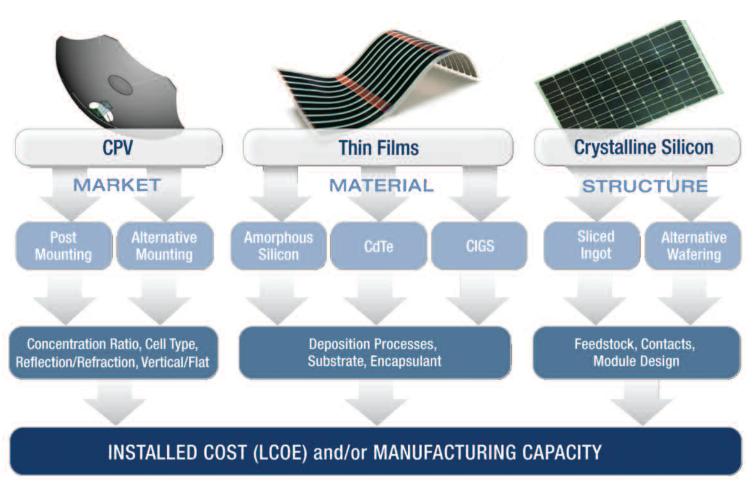

Figure 5. **Photovoltaic technologies differentiated by material, manufacturing technique, and engineering designs.**

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Table 1. **Key areas of differentiation in photovoltaic technology.**

Crystalline Silicon

Key areas	Examples
Ingot Crystal Structures	• Multicrystalline • Monocrystalline
Wafering Techniques	• Wire sawing • Pulling slices off the ingot through strategic ion implantation
Cell Contacts	• Screen-printing conventional contacts • "Emitter wrap-through" contacts that come up through the cell • Inkjet printing conventional contacts
Feedstock Choice	• "Solar grade" feedstock • Integrated circuit stock material

Thin Films

Key areas	Examples
Active Material	• Copper indium gallium diselenide (CIGS) • Cadmium telluride (CdTe) • Amorphous silicon (a-Si)
Method of Deposition	• Physical and chemical vapor deposition • Atmospheric deposition, such as ink printing or electroplating
Substrate	• Glass sheets • Stainless steel web • Polyimide

Concentrating Photovoltaics

Key areas	Examples
Concentration Ratio	• Two suns • 1000 suns
Cell Type	• Wafer reuse to decrease utilization of expensive germanium • Low concentration using crystalline silicon or thin film cells
Lens Type	• Fresnel • Dome-shaped
Module Mounting	• Very large module assemblies stuck on posts • Low to the ground "carousel" assemblies
Number of Axes a Tracker Uses	• One axis tracking • Two axis tracking
Module Design	• Postage-stamp sized cells • Miniature assemblies of microconcentrators

ingot from a melt of high purity silicon, slice it into wafers, process the wafers into active photovoltaic cells, encapsulate the cells within a top cover glass, transparent adhesive, and a flat, rectangular backsheet, frame it with aluminum, and attach a junction box which connects the cell contacts with the outside electrical leads. Key areas of differentiation are the use of distinct ingot crystal structures, alternate wafering techniques to slicing, cell contacts, and feedstock choice.

Thin film photovoltaics represent the rest of today's photovoltaic market. The three technologies currently commercialized use amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). The general idea behind thin film photovoltaics is that depositing thin layers of light-absorbing photovoltaic active materials on low-cost supporting substrates will be a cheap, quick, scalable way to mass-produce photovoltaic modules. Product variations are largely determined by choice of active material, method of deposition, and substrate.[4]

Though CPVs do not currently claim significant market share, they are a technology with strong potential to enter the growing market for photovoltaic solutions.[5] The concept of CPV is to use lenses and mirrors to direct multiple suns-worth of light onto a photovoltaic cell, thereby boosting its electrical output. The typical photovoltaic cell is a multijunction cell usually made of semiconductor materials from the Periodic Table groups III and V**. The cells are relatively small (1 cm^2) and more costly, yet very efficient. The multiple junctions allow the cell to convert more of the sun's light spectrum to electricity. The extra expense of III-V cells requires concentration and sun-tracking to make this technology cost-effective. Multijunction cells are manufactured by depositing III-V materials through metal organic vapor phase epitaxy on germanium wafers. Processing variables in the CPV space include concentration ratio, cell type, lens type, module mounting, number of axes a tracker uses, and module design.

Photovoltaic Manufacturing Scale-up

Price decreases will also come after the photovoltaic industry has reaped the benefits that large scale manufacturing provides. Figure 6 shows the module price for crystalline silicon plotted versus cumulative production for the crystalline silicon photovoltaic industry. This type of graph, called an "industry learning curve," represents the collective progress of the manufacturing industry, including its supply chain.

As individual companies make improvements and suppliers become more efficient, many of these advances will diffuse or "spill" across the industry and lower the costs of production for all. As the graph shows, silicon photovoltaics have been steadily decreasing in price since the 1980's. The cost to the company to make the photovoltaic module is consistent with the price the company charges when a 30% profit is assumed. Therefore, the trend in prices is generally assumed to reflect the trend in costs. Using wire saws, for instance, allowed silicon wafer manufacturers to slice hundreds of

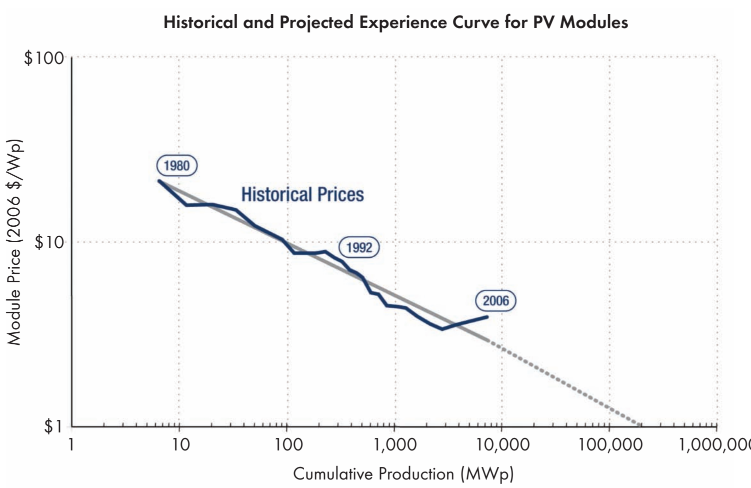

Figure 6. **The average module selling price for crystalline silicon photovoltaic modules as a function of the industry's cumulative production.**

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thinner wafers simultaneously, increasing material utilization which dramatically increased throughput. This advance was widely copied throughout the industry, allowing all wafer manufacturers to progress down the learning curve and therefore decrease the cost of modules.

Regardless of whether the technology group is crystalline silicon, thin films, or CPV, the manufacturer's suppliers are positioned in particular to introduce high impact innovations and advances across the industry. The maturing of the industry will also bring increased standardization. The model to emulate is the semiconductor industry, which has a highly organized set of manufacturing standards that allows suppliers to more efficiently serve their manufacturing customers.[6] All of these advances will enable beneficial scale-up of manufacturing and widespread cost decreases in photovoltaics.

SUMMARY

As the cost of photovoltaics continues to decrease, it will become a boon to defense communities as the levelized cost of energy from a photovoltaic system hits the point of grid parity. The metric levelized cost of energy provides a useful way to compare electricity from a photovoltaic system and electric rates so that we will recognize when the US has hit the point of grid parity. Through the rich diversity of module photovoltaic technology and the lessons that the industry will learn as it scales up production, the era of cheap photovoltaics will soon be arriving. Until then, there is still a strong rationale for using photovoltaics in the military because of increased self-sufficiency.

NOTES & REFERENCES

* For more information on the DOE's Solar Energy Technologies Program, please visit: http//www1.eere.energy.gov/solar/.

† *N* is the lifetime of the system in years, the discount rate is a financial term that corrects for the change in the value of money over time and includes the opportunity cost of buying a photovoltaic system instead of investing money elsewhere, and the other variables are described in the equation.

‡ Assumptions: For the price of electricity, the average electricity price for the 1000 largest utilities in the US based on Energy Information Agency data for 2006 (except CA, where existing tiered rates structures were used). The installed system price is set at $8.5/Wp in the current case and is assumed to be financed with a home equity loan (i.e., interest is tax-deductible), with a 10% down payment, 6% interest rate, the owner in the 28% tax bracket, and a 30-year loan/30-year evaluation period. The solar performance (electricity generated) is based on the National Solar Radiation Database (NSRDB) weather station closest to the center of the utility service territory, assuming a south-facing array, at a 25 degree tilt. An 82% derate factor is used to account for inverter and other photovoltaic system losses, but no performance degradation over life of the system is assumed. Incentives included are the federal Investment Tax Credit (ITC) worth $500/kW due to $2000 cap and individual state incentives as of December 2007. The federal ITC has been revised to no longer have the $2000 cap; therefore these forecasts may be more conservative than initially calculated.

§ Assumptions: Same as previous map, excepting the use of installed system price of $3.30/Wp, real electricity rate increases of 2.5% per year (22% total since 2006), and no inclusion of incentives. Also note the current federal solar subsidy provides a tax credit for 30% of the installed system price and is scheduled to expire in 2017.

** Groups III and V are the elements that occupy columns IIIA, IIIB, and V of the Periodic Table. The most common semiconductors among these elements include scandium (Sc), yttrium (Y), vanadium (V), niobium (Nb), and tantalum (Ta).

[1] Gartner, J., *Washington Times*, 2004.
[2] ALOG NEWS, *Army Logistician*, PB 700-05-03, Vol. 37, No. 3, May-June 2005.
[3] Sandia National Laboratory press release, 2006.
[4] Noufi, R., K. Zweibel, *NREL Report No. CP-520-39894*, 2006.
[5] Kurtz, S., *NREL Report No. TP-520-43208*, 2008.
[6] *Renewable Energy World*, Vol. 10, No. 3, May/June, 2007.

Dr. Marie Mapes is a photovoltaic technology manager in the US Department of Energy Solar Energy Technologies Program. Her current responsibilities include coordinating photovoltaic R&D at the National Renewable Energy Laboratory and Sandia National Laboratory, managing university research in advanced photovoltaic concepts, and arranging partnerships between industry, universities, and national labs wherever possible to maximize DOE's research investments. She entered DOE in 2006 as a Presidential Management Fellow. During her two year Fellowship, she initiated new program activity to capitalize on innovative financing mechanisms for solar technology in the federal sector (such as power purchase agreements), launched the Next Generation PV Device and Processes awards for universities and start-up companies, and explored private sector investment strategies during a four month detail at NGEN, a cleantech venture capital firm. Before coming to DOE, Dr. Mapes earned a PhD in Physical Chemistry from the University of Wisconsin-Madison, where her research focused on stability of amorphous systems with applications in the shelf-life of pharmaceuticals. Her undergraduate institution was Grinnell College, where she earned a BA in chemistry.

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